Understanding geolocation and navigation and their uses in Precision Agriculture

It is said that GPS triggered Precision Agriculture (PA), allowing the first yield maps to be created. That may or may not be precise but what is true is that the use of global positioning systems has boosted PA, offering many current profitable applications at the fingertips of farmers, researchers and other agricultural stakeholders. From the first GPS receivers (around 1976) to the current global navigation satellite system devices only 40 years have passed. In this period, manufacturers have reduced the receivers' size several thousand-fold, they have lowered their cost and have exceeded their capabilities beyond imagination. In this 2nd Precision Ag Corner section we will discover how to take advantage of positioning and navigation systems in the framework of PA. The Research Group in AgroICT & Precision Agriculture (GRAP) of the University of Lleida-Agrotecnio Center in Catalonia, Spain has the story.

THE MOST COMMON positioning system in occident is the GPS. However, there are three other global systems currently available: the Russian GLONASS, the Chinese BeiDou and the recently activated European GALILEO (operating since December 15th 2016). Using the term GPS implies dismissing the other three. The generic term is GNSS (global navigation satellite system) and should be used to refer to receivers in general or to receivers operating with more than one system. Modern and accurate receivers are hardware-ready to receive signals from more than one GNSS as the more available satellites, the more accurate the positioning. In Figure 1-left we show one of the first military GPS receivers used to test the system and to validate other equipment (such as the portable unit in the centre). On the right, we show a miniature GNSS receiver (16x16x6.8 mm, antenna included!) able to receive radio signals from satellites of the GPS, GLONASS, GALILEO and BeiDou constellations.

WHEN IS GNSS USED?

Global navigation satellite systems consists of three subsystems called segments: 1) the space segment, 2) the control segment and 3) the user segment. The spatial segment includes the satellite constellations orbiting around the globe (hence the term global). The number of orbital planes and satellites and their altitude is slightly different for each of the four GNSS. The control segment includes all the ground-based elements to monitor and control the space segment. Finally, there is the user segment, including the receivers, the antennas and their applications.

As introduced in the 1st Precision Ag Corner (New Ag International Nov/Dec 2016), GNSS receivers are used in the first stage of the map-based PA cycle, 1-Data acquisition, to document observations with the position coordinates. They are also used in the last stage of the cycle, 4-Actuation in the field, either to document machinery actuation or for site-specific management purposes. However, georeferenced data are used in the second stage (2-Information extraction) and the third stage (3-Decision making). In addition to document geolocation of data or machinery or operations, positioning systems together with software applications allow navigation to be implemented. Navigation is used for machinery displacement within the field following a specific path, for sampling purposes at specific locations and for site-specific management. In conclusion, GNSS receivers are technology-based solutions to help understand agronomic data spatial variability, make better agronomic decisions and putting them into practice on a site-specific basis.

DETERMINING THE POSITION OF A RECEIVER

Putting it simply, satellites emit

Figure 1: One of the first military GPS receivers used as a generalized development model manufactured by Rockwell Collins around 1977 (left, adapted from GPSWorld). A Magnavox manpack GPS unit of 25x45x15 cm and more than 11 kg showed in the very first GPS receiver catalogue in mid 70s (centre, adapted from GPSWorld). A miniature GNSS complete receiver (including the antenna!) launched in 2012 of 16x16x6.8 mm and 6g (right, adapted from Globaltop Technology Inc.).

radio signals with embedded information. Part of the information emitted is the exact location of each satellite in a geocentric reference system and it is decoded by the receiver. Additionally, those radio signals are also used to determine the distance from the receiver to each of the tracked satellites. Without entering into details, time and clocks in the satellites and in the receiver are key elements to estimate the so-called pseudo-ranges (distances between the receiver and the satellite including errors). Once the position of each satellite and the distance to the receiver is known, a process called 3D trilateration is applied. If a Satellite A is located in the space at (X_A,Y_A,Z_A) and the distance to the receiver is R_A, then the receiver can only be located on a sphere S_A of radius RA centred at the satellite location (X_A,Y_A,Z_A). The intersection of the sphere SA with the Earth as a circle meaning that the receiver could only be located anywhere on the circle on the Earth surface. If a Satellite B is also tracked, the intersection of the sphere S_B with S_A and the Earth results in only two possible locations of the receiver. A third sphere, S_C, would result in a unique solution for the location of the receiver. Ideally (without considering errors in the distance estimations), only 3 satellites are required to determine the three unknown coordinates of the position of a receiver on Earth (X_R,Y_R,Z_R) as each satellite provides the receiver with an equation to solve the problem. However, in the real situation there is a fourth unknown which is the time difference between the GNSS (as a system) and the receiver. That means that a fourth equation, provided by a fourth satellite, is required to determine the three coordinates. Nevertheless, when only three satellites are available there is always the possibility to obtain a 2D position for the receiver (X_R,Y_R).

SOME ERRORS AFFECTING ACCURACY

Trilateration is based on the accurate knowledge of the actual position of the satellites and on the distance between them and the receiver, which is estimated using accurate timing. Therefore, three main groups of errors can affect position estimation accuracy. 1) Errors in the position and the clocks of satellites; 2) Errors in the radio signal propagation from the satellites to the receiver; and 3) Errors in the clocks and calculations of the receivers. Some of these errors can be corrected and some cannot. One of these errors is the effect of the ionosphere in the radio signals propagation, which can be corrected. The total electron content in the ionosphere delays signals according to its frequency. Dual frequency receivers are ready to receive two of the several radio signals emitted by satellites and by comparing the delays in the two signals are able to estimate the error of the ionosphere in the distance estimation. That is why dual frequency receivers are much more accurate than single frequency receivers, as the latter use a model to correct the ionospheric effect. Another error concerns the relative position of the tracked satellites in the sky, the so-called dilution of precision (DOP). The closer the satellites are to one another, the higher the DOP and hence the error. Using receivers sensitive to more than one GNSS constellation will make many more satellites available for them to choose the configuration minimizing the DOP.

The error of stand-alone receivers (without any external correction) is of several meters (some more in elevation), that is why correction systems are required to lower it down to some centimetres. As a curiosity, the time retrieved by receivers from satellites is one of the most accurate measurements of time available to the general public and it is used for clock and sensor synchronization in many professional applications.

THE REQUIRED ACCURACY: FROM 5 CM TO 20 M, DEPENDING ON THE OPERATION

First of all, it is important to clarify the terms accuracy and precision. When it comes to sensing, accuracy is the quality of a sensor to provide readings close to the actual values. In GNSS receivers it is to be distinguished between relative accuracy and absolute accuracy. Relative accuracy is the ability of a receiver to provide accurate positions of the same waypoint within a short time interval (e.g. between two passes of a tractor). It is also known as pass-to-pass accuracy or short-term accuracy. Absolute accuracy is the ability of a receiver to provide accurate positions of the same waypoint within longer time intervals (e.g. weeks, months or years). It is also known as year-to-year accuracy or long-term accuracy. When readings are taken in few minutes' difference, the satellites used and the atmospheric conditions will be very similar as will the errors for the position estimation. When readings are taken at very different moments,

Table 1: Recommended accuracy for several agricultural operations.

Operation	Recommended accuracy
Field identification	±20 m
Identification of zones within a field Soil sampling and Yield mapping	±1 m
Generic tillage Uniform spraying and fertilizer spreading	±30 cm
Variable rate spraying and spreading Sowing and mowing	±10 cm
Tractor guidance Seedbed preparation	±5 cm
Precision sowing and transplanting Guidance for inter-row and in-row operations	< ±5 cm

Table 2: GNSS receiver accuracy according to the specifications and the augmentation system

ACCORDING TO ↓	LOW ACCURACY (error >> 1m)	MEDIUM ACCURACY (1m > error > 5cm)	HIGH ACCURACY (error < 5cm)
GNSS CONSTELLATIONS	Only 1 (usually GPS)	Multi-constellation (GNSS)	Multi-constellation (GNSS)
RECEIVER FREQUENCY	Single frequency (L1)	Dual frequency (L1+L2)	Dual frequency (L1+L2)
AUGMENTATION SYSTEM	Stand-alone (no correction)	Some public and private SBAS and GBAS	Some private SBAS and GBAS and RTK

An Interview with...

IGNACIO ROSSI, Regional Sales Manager Mediterranean Ring, Trimble Agriculture EMEA

GPS and GNSS were considered to be catalysts for Precision Agriculture (PA) in the late 80s. What is the situation today and what is the future of GNSS in agriculture?
GNSS, Global Navigation Satellite System (including GPS, GLONASS and other satellite networks) were and are still critical for Precision Agriculture to provide positioning for almost all applications. In the early days, GPS receivers were used for rough positioning in fields, guidance, scouting fields and yield monitoring maps. With GNSS developments and a higher level of accuracy, easier and more affordable correction services in addition to more advanced and accurate guidance and machine control systems, agriculture applications alternatives are increasing continuously.

What is the size of the world market for Ag GNSS devices and how is the market segmented between RTK (2cm precision) and 30-50cm accuracy?
We don't have stats precise enough to share with the media on that. However, the market is steadily adopting more high accuracy solutions as costs come down and availability of high accuracy signals such as Trimble RTK and CenterPoint RTX increases. Adoption grew significantly when RTK-like performance was made available via satellite delivery [with CenterPoint RTX] since its signal can reach receivers almost everywhere in the world and it is not reliant on the receiver's proximity to a ground-based correction station.

Are there new technologies around the corner to reduce the cost of the 2cm precision?
Yes. New technologies are reducing cost for accurate solutions. Trimble was the pioneer that developed in 1992 RTK (Real Time Kinematics) which required base station + rover, both with radios. Later Trimble developed solutions with VRS for rovers to be connected to the network with a modem. Recently Trimble was also a pioneer in developing CenterPoint RTX with centimeter accuracy corrections via a specific satellite correction signal without base station, radio or modems. In addition, the latest guidance hardware developments and integration with machines helps to reduce cost for the overall solution. In summary, today it is possible to use Trimble Autopilot for high repeatable accuracy for about one quarter of the cost that it was 10 years ago.

What is the dominant usage of guidance systems: section control to reduce overlapping, yield mapping or variable rate inputs?
Most typical precision agriculture applications depend on the technology adoption level for each country or region. This needs to be in line with machinery available demand for different crop productions. Most dominant precision agriculture solution demands are related to guidance systems. They could be used to reduce overlapping, improve ergonomics and work efficiency for almost any type of agriculture application and most types of tractors. During the last few years, with sprayers and spreaders modernization process, section control and variable rate control solutions led to an increased demand for technologies adoption. Still variable rate applications have had low levels of adoption, compared with guidance solutions which in some markets account 40-50% adoption.

Regarding other PA technologies, even though research in PA started in the late 80's, it is currently not widely implemented at the farm level. What are the main reasons explaining this situation? What is required from all-stakeholders to increase PA adoption?
In my opinion, varying levels of technology have been available to farmers for a long time. Early adopters and advanced farmers have been implementing precision agriculture in the most important agricultural regions since years ago. One of the major barriers is not with technology or the cost itself, but with cultural barrier to changes. Investments in precision agriculture solutions have actually decreased, compared with the proven benefits farmers can get in return such as: input savings, improved efficiency and reduced environmental impact. For example, the investment in guidance is small compared to tractor value and could help with cost savings for some machines. In some cases, a barrier to increased use of precision agriculture is the required agronomic knowledge that is needed for solutions or technology packages that include VRA and site-specific management. Sometimes the barrier is the government not showing the benefits of new technologies that improve efficiency and reduce environmental impact for the whole region. In EU, a current CAP subsidies programme is supporting "innovation" in most countries and this could be one way to support technology adoption.

Yield maps are one of the first "hints" of PA helping farmers realize that their yields might not be as uniform as expected. However, it seems many farmers and service providers are not really using them to their full potential. Do you agree? If so, what may be the reason behind such a situation?
Crop yield maps are definitely a good starting point for precision agriculture solutions. They can show yield variability and information about fields that farmers need for decision making with their advisors. At the same time yield maps on their own may not be enough to explain all scenarios. Farmers sometimes need additional soil sampling information, satellite images or aerial pictures to create an index such as NDVI to complete the analysis. In addition, the actual use of yield maps by farmers is growing

due to the fact that these additional pieces of data that are mentioned above are becoming more available and increasingly affordable.

Trimble products help farmers be more efficient in applying agricultural inputs. What is the relationship of Trimble with manufacturers and suppliers of agricultural inputs (i.e. irrigation water, fertilizers, crop protection products, biostimulants and micronutrients,)?
Trimble Agriculture is brand agnostic and works with many Ag machinery manufacturers. We are capable of supporting most of the popular brands and solutions available in the market or even to develop specific advanced protocols that many manufacturers adopt due to the simplicity to become compatible with Trimble systems in the field. One good example is TUVR (Trimble Universal Variable Rate) which is a protocol implemented by many important OEMs for their controllers. It allows them to control the rate and sections on their machine controllers based on VRA maps loaded on Trimble displays.– We also partner with various implement manufacturers and Ag input suppliers to integrate specialized software applications, or "apps", into our precision farming displays such as the TMX-2050 display. This allows farmers to access data or functionality specific to that manufacturer's products.

When small or medium farmers hear about PA some immediately say it is not for them, that it is only useful in big farms in highly developed countries. What would you tell them?
Precision agriculture can be implemented in all different types and sizes of farms, with the solution mix and use varying based on the farm needs. Although farm size matters, it is not the most important factor. There are some intensive and small production farms with vineyards or orchards that can use precision agriculture products or remote sensors to then work with variable rate applications considering soil, crop health status and even selective harvest. In farms like these that need to apply chemical treatments multiple times per year, precision agriculture management pays off and is not considering traditional "guidance with GPS". Most of the time, even with minimal precision agriculture technology adoption, farmers will be able to be more efficient. Trimble's product portfolio addresses these different farm and application needs with a variety of solutions and prices for the different sized operations.

A focus group of the European Commission pointed out that PA usually means high initial costs and long return-on-investment periods. Is PA technology "too expensive"? Are there independent cost-benefit studies analysing the actual payback of PA implementation?
Investments in precision agriculture need to be according to application, operation size and agriculture activity, as each farm requirements can be different. For a medium size operation, technology components required for guidance or to implement VRA could be a fraction of the cost of the tractors and machines used for these applications. At the same time, PA could help to increase yields and productivity and reduce production cost in short term fuel and input costs. Return on investment for PA can be high compared with traditional technologies operations of the same size. There are multiple independent studies, typically done by universities, for precision agriculture on specific local productions or conditions. I encourage farmers to approach local research institutes or agronomists that have done trials. However, the best examples are actual farmers' experiences. Farmers who have adopted precision agriculture technologies, after a while upgrade their machines or systems to add even more solutions because they see the benefits.

What are the principal challenges of PA in the coming years? How is Trimble getting ready to face them?
There are still some challenges with cross-brand (cross-manufacturer) hardware compatibility that Trimble is working to solve with its TUVR protocol and ISOBUS development efforts. The next biggest challenge is PA data format compatibility, or lack thereof. There are various industry groups formed to bring all of the manufactures together to agree on a common data format that can be used across platforms. Trimble participates in many of these forums, but has already been supporting many data formats within our Farm Works and Connected Farm software; now known as Trimble Ag Software.

neither the satellites nor the atmosphere will be similar and errors will be larger if not corrected. Relative accuracy values are better than absolute accuracy and they are sometimes confused in catalogues.
Precision is a term related to the ability of the sensor to provide readings close to one another when the parameter under measurement remains constant. Therefore, what one may expect from a GNSS receiver is high accuracy (i.e. location solutions close to the actual location) and good precision (i.e. the dispersion or variability in the location solution kept as low as possible). But that is impossible to achieve with stand-alone receivers and correction or augmentation systems are needed to improve the receiver performance.
But what is the required accuracy? Is sub-metre accuracy good enough? Do we always need centimetre errors? The answer is it depends. It depends on what we are intending to do and, of course, on our budget! In Table 1 there is a non-exhaustive list of agricultural tasks and the recommended accuracy gathered from research and professional publications.

AUGMENTATION SYSTEMS

To achieve such accuracy external systems to the receivers and GNSS are needed. They are called augmentation systems and can be classified in two groups: satellite-based augmentation systems (SBAS) and ground-based augmentation systems (GBAS).
The concept is similar in both groups as it is based on the use of a fixed antenna in an accurately known location to determine the bias error of the position estimations. The antenna receives the radio signals from the satellites and a receiver determines its location in a similar way a convention-

al receiver would do. The difference is that the location determined using the satellites is then compared to the actual location of the antenna so that the absolute error can be calculated for each estimation. Such error is used to create a correction message and is sent to the receiver whose position needs to be corrected (called rover). When using the American system, it is then said that the corrected location is determined by differential GPS or DGPS. The closer in space and time the fix antenna and the rover are, the more accurate the correction since the satellites and the atmospheric conditions will be similar. In real conditions, augmentation systems use a network of fixed antennas that provide generic or tailored correction messages within a territory. In a SBAS, the correction messages are uploaded to specific satellites to broadcast them to the enabled receivers in its area of influence.

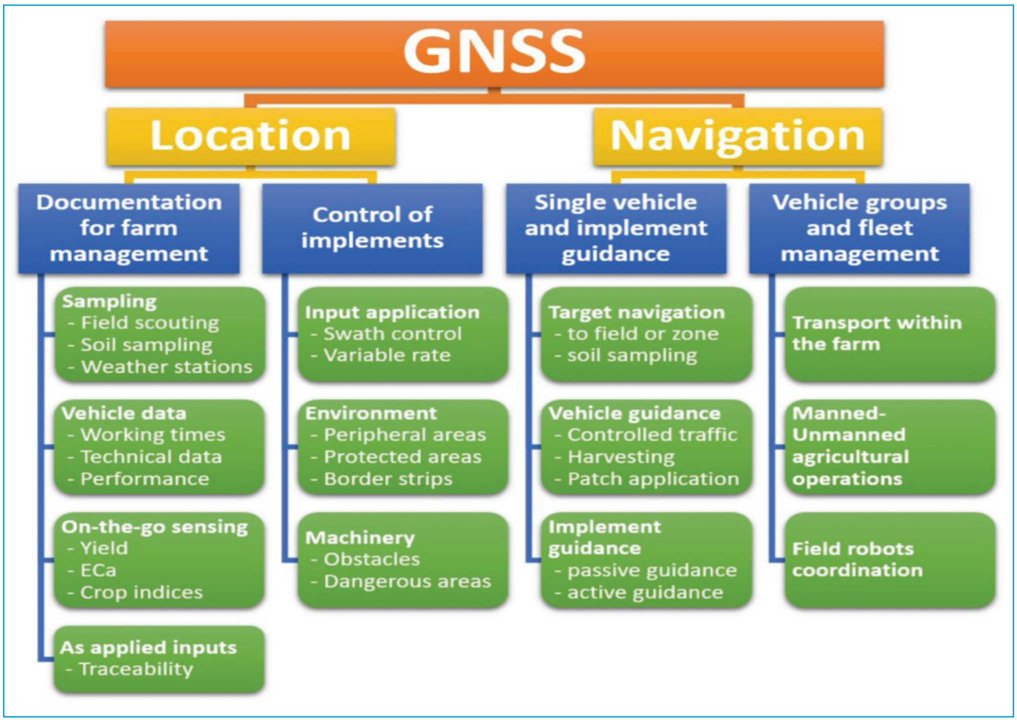

Figure 2: GNSS applications in agriculture (adapted from Auernhammer, H., 2001. Precision farming - the environmental challenge. Computers and Electronics in Agriculture 30, 31-43).

In a GBAS, the correction messages are broadcasted by terrestrial communication networks such as radio stations, internet, mobile data communications (GPRS) and Wi-Fi. In both groups public and private solutions are available. EGNOS and WAAS are well-known public SBAS for Europe and North America, respectively. Their absolute accuracy (year-to-year) is less than 1m while their relative accuracy may be less than 50cm. In order to take advantage of SBAS, receivers should be able to receive an additional radio signal from the SBAS satellites containing the correction messages. Private SBAS solutions can lead to sub-decimetre accuracy (e.g. Omnistar products or Atlas from Hemisphere). GBAS can provide less than 5cm accuracy when virtual stations are created to provide users with personalized corrections once the rough position of the receiver is known. For this purpose, receivers should include radio-modems, GPRS mobile modems or Wi-Fi connection to communicate with the correction message provider server. The most accurate current solution is the so-called RTK (real-time kinematics) GNSS. This system is equivalent to a GBAS with the singularity that the user owns two receivers. One is used as a fixed base stationed in known coordinates and the other is used as a rover. The two receivers are connected by a radio link. The base station produces and sends correction messages to the rover to achieve about 2cm accuracy since the satellites used and the atmosphere are exactly the same in both receivers and correction messages nearly correct all the errors. To conclude, accuracy and precision in receivers is summarized in Table 2.

GNSS USE IN AGRICULTURE: FOR DATA ACQUISITION TO START WITH...

GNSS data plays an important and diverse role in Precision Agriculture (Figure 2). In map-based Precision Agriculture, maps are created to display and analyse the spatial and temporal variability of agronomic variables. At that stage of the PA cycle, GNSS applications are related to Data acquisition. Receivers are then used to georeference collected data from the crop or soil within the field. Georeferencing is the process of documenting agronomic data with position coordinates. Such data may come from field scouting for visual assessment of crop performance and pests or diseases, from crop or soil sampling and from readings of sensors either handheld or moved throughout the field with a vehicle. The location of these data will help in the creation of records for the farmer himself or to be forwarded to an advisor (or vice versa). Additionally, when data is collected with sufficient spatial resolution, it can be used to create maps of the agronomic parameter spatial distribution. The required spatial resolution depends on the size of the field and on the variability of the sampled parameter and may range from one sample per hectare in grid soil sampling upto several hundreds of readings per hectare when it comes to on-the-go electronic sensing. Alternatively, data collection may be designed at the office (targeted sampling) so receivers will then be used to navigate to specific sites for crop or soil sampling. That is also the case of unmanned aerial vehicles taking pictures of the crop following specific flight plans.

Additional data may be collected from the agricultural machinery itself. Tractors are currently equipped with several dozens of sensors. When connected to position data from GNSS receivers, it is possible to locate all the tractors of the farm, to know their working parameters in real time (telemetry) and to subsequently analyse the overall performance during specific agricultural operations. In a similar way, modern equipment is also fitted out with sensors that together with receivers may be used to extract information on the performance of agricultural operations and the agreement with the designed action within the fields (i.e. applied doses of fertilizer, pesticide, herbicide or even irrigation). The resulting data can be displayed in a so-called as-applied map, a very useful tool for documentation purposes and traceability. That can be done both in map-based PA and in real-time sensor-based PA.

....BUT ALSO FOR ACTUATION IN THE FIELD

After the second stage (2-Information extraction) and third stage (3-Decision making) of the map-based PA cycle it is time to work in the field (fourth stage: 4-Actuation in the field). GNSS receivers and controllers are boarded on agricultural machinery to know their position and 1) adjust the equipment for site-specific management or 2) to navigate to specific locations. For the former, prescription maps need to be preloaded in the controller. GNSS receivers and controllers put together actions to be carried out at specific locations in the field (site-specific management). When positions acquired from a receiver are represented in the map, the controller retrieves the corresponding action. When risk maps are loaded, the site-specific actions may be a no-action command (e.g. no application of fertilizer or pesticide in specific areas to protect water). Another kind of GNSS-based product is what is known as swath control. When implemented in fertilizer spreaders, sprayers or even in sowing machines, the controller records the areas in the field where the agricultural input has already been applied, with the help of the receiver. If the equipment passes over an area